Research on Low Carbon Transformation of Manufacturing Supply Chain - Based on Evolutionary Game Model

Wei Zhang[1,a], Hua Bian[2,b*]

{zhangw@cqupt.edu.cn[a], 1262467922@qq.com[b*]}

School of Economics and Management[1], School of Modern posts[2], Chongqing University of Posts and Telecommunications, Chongqing, China

Abstract. In order to explore the strategic choices of the members of the innovation coordination system during the low carbon transformation of the supply chain, an evolutionary game model of the low carbon transformation of the regional manufacturing supply chain involving local governments, supply chain enterprises, and low carbon technology enterprises was constructed, employing the concepts of evolutionary game theory. In addition, a numerical simulation analysis using MATLAB was performed. The results of the analysis revealed that: the improvement in financial and green performance brought about by low-carbon transformation can effectively stimulate the low-carbon transformation of the supply chain; government subsidy and punishment policies can also effectively promote the low-carbon transformation process of the supply chain, and as the level of punishment rises, the government and supply chain enterprises evolve to a stable point at a faster rate; various entities have different sensitivities to parameter changes.

Keywords: Manufacturing supply chain; Low-carbon transition; Evolutionary game

1 Introduction

With the process of industrialization, people's expectations gradually changed from "hoping for food and clothing" to "looking forward to environmental protection", the demand for low-carbon products increased, and the customer requirements faced by enterprises became more complex [1]. At the same time, with the change of climate, corresponding policies have been introduced one after another, and the business regulations faced by enterprises have become stricter. In this case, manufacturing enterprises have to move towards the path of low-carbon production, but in order to carry out low-carbon production and meet the requirements of environmental protection organizations that affect their operations, enterprises have to make additional investment[2] in low-carbon technologies, which has caused tremendous cost pressure on enterprises. The problem of low-carbon transformation cannot be solved by enterprises alone. It is necessary to jointly supervise [3] through cooperation between upstream and downstream enterprises and the formulation of corresponding policies by the government, so as to organically combine the economic and environmental benefits of enterprises. In other words, the low-carbon transformation of the supply chain is imminent. It is worth noting that although the low-carbon transformation requires huge costs, it can also significantly improve

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the profitability of manufacturing enterprises. In this process, innovation investment and easing financing constraints are very important mechanisms [4].

In the low-carbon supply chain transformation, low-carbon technologies have a significant positive impact on the performance of manufacturing enterprises, and their development and application are of paramount importance. Li M et al.'s research shows that [5]in the process of low-carbon supply chain transformation, low-carbon technology research and development and reputation play a mediating role. Low-carbon supply chain transformation can significantly improve carbon and financial performance, and support from local governments can significantly promote low-carbon supply chain transformation. At present, R&D of low-carbon technologies has achieved some results, such as carbon capture and storage technology. Through the implementation of decarbonization strategies in both existing and new fossil fuel power plants, and the development of low-carbon fossil fuel blue hydrogen, ammonia, and hydrogen demonstrate immense potential as carbon-free fuels, thus providing a broad range of application prospects in the energy sector. In particular, hydrogen has been highly anticipated as a driver of a carbon-free economy. However, there are huge gaps in the application or diffusion of technology, and low-carbon service providers have responded. Many scholars have carried out corresponding research [6].

As the largest developing nation globally, China possesses a distinct socialist market economic structure. In the process of low-carbon transformation of the manufacturing supply chain, it needs to exert its unique advantages: state-owned enterprise[7] can use its advantages in market position and basic resources to promote the low-carbon transformation of upstream and downstream enterprises in the supply chain through competitive selection mechanism, supply and demand matching mechanism and resource coordination mechanism. In the future, China will take low-carbon investment as an important breakthrough point for stabilizing economic policies[8], and promote the low-carbon transformation of China's manufacturing supply chain through various measures such as product upgrading and carbon reduction, using usable materials to reduce carbon, technological innovation to reduce carbon, space optimization to reduce carbon, and efficient management to reduce carbon. [9]. At the same time, it should be noted that government subsidies [10] can effectively stimulate the innovation practice of enterprises, and have a positive effect on the green performance and financial performance of enterprises. And government intervention can effectively guide manufacturing enterprises to shift to low-carbon innovation, thereby promoting the low-carbon transformation.

At present, how to use effective policies to achieve regional low-carbon growth and coordinated development among regions is an urgent and critical issue. In light of the aforementioned analysis, the current study proposes a tripartite regional coordination system, consisting of supply chain enterprises, low carbon service providers, and local governments. Employing the theoretical framework of evolutionary game theory, the paper endeavors to explore the intricate evolutionary mechanism involved in the low-carbon transformation of manufacturing supply chains.

2 Problem description and model assumptions

This paper focuses on the collaborative behavior of the three types of participants in the low-carbon transition coordination system, and examines the co-creation mechanism among the various players. The coordination relationship between stakeholders is a bounded rational behavior game. Each party chooses a strategy based on its own profit and loss, which is influenced by the behavioral choices of the other two parties, and will also affect the strategic choices of the other two parties. The low-carbon transition of the supply chain is a long-term and complex dynamic process. Evolutionary game is aimed at the bounded rational game subject, combining game analysis with dynamic evolution.

Assumption 1: Participating entities, government departments as Participating Entities 1, are the promoters of the green and low carbon transformation of the supply chain. Manufacturing supply chain enterprises (MSCE), as participating entities 2, are mainly responsible for integrating advanced green and low carbon technologies. Low carbon technology enterprises (LCTE), as participating entities 3, mainly provide corresponding green and low carbon transformation services for manufacturing supply chain enterprises, including but not limited to advanced green and low carbon technologies, low carbon transformation solutions, etc. All three parties make decisions with bounded rationality.

Assumption 2: In a coordinated strategy, the probability of the government choosing to regulate is $x(x \in [0,1])$, the probability of the corresponding choice not to regulate is $(1-x)$, the probability of the low-carbon technology enterprise choosing to actively participate is $z(z \in [0,1])$, the probability of the corresponding low-carbon technology enterprise choosing to participate in the negative participation is $(1-z)$, the probability of the manufacturing supply chain enterprise choosing to participate in the low-carbon transformation is $y(y \in [0,1])$, and the probability of the corresponding manufacturing supply chain enterprise choosing not to participate in the low-carbon transformation is $(1-y)$.

Assumption 3: Cost. When the government chooses a regulatory strategy, it will sign a contract with MSCE to supervise the green and low carbon transformation process of the supply chain, and the supervision cost is C_3. When MSCE choose to participate in the green and low carbon transformation strategy, they must bear the introduction cost of green and low carbon technologies C_1, including but not limited to technology purchase, equipment introduction, workshop renovation, etc. When low-carbon technology companies choose to participate actively in the strategy, their input cost is C_2, such as R&D expenses for research and development of advanced low-carbon technologies, and their input cost when choosing a passive participation strategy is$\gamma C_2(\gamma \in (0,1))$. In order to promote the low-carbon transformation of the supply chain, the government will provide $mC_1(0<m<1)$ and $nC_1(0<n<1)$ cost subsidies for MSCE and LCTE, respectively, Where m and n are the cost subsidy coefficients provided by the government.

Assumption 4: Benefits. When MSCE choose to participate in the green and low carbon transformation strategy, and LCTE choose to actively participate in the strategy, the basic benefits obtained by MSCE and LCTE in the green and low carbon transformation are R_1 and R_2, respectively. At this time, the government can obtain certain credibility benefits and the green economic benefits L brought by the green and low carbon transformation of the supply chain. When MSCE choose to participate in the green and low carbon transformation strategy, and LCTE choose to participate passively, the benefits obtained by MSCE and LCTE in the green supply chain transformation process are $\alpha R_1(0<\alpha<1)$ and $\beta R_2(0<\beta<1)$, respectively. At this point, the government can reap certain credibility benefits and green economic benefits $L_1 (L > L_1)$ from the green and low carbon transformation of the supply chain.

Assumption 5: Punishment. In order to promote the low-carbon transformation of the supply chain, the government will levy taxes on MSCE that are unwilling to participate in the low-carbon transformation, including but not limited to carbon taxes, environmental pollution penalties, etc. At the same time, if MSCE do not participate in the low-carbon transformation, they will suffer potential losses, including but not limited to the reduction of technological innovation and the increase in costs caused by problems such as resources or innovation. Presuming the aforementioned stipulations, the summarized evolutionary game income matrix of MSCE, LCTE, and the government is depicted in Table 1:

Table 1. Payment matrix

Participants				Low carbon technology enterprise	
				Actively participate z	Passive participation $1-z$
Government	Supervision x	Supply Chain Enterprise	Low Carbon Transition y	$R_1 - C_1 + mC_1$ $R_2 - C_2 + nC_2$ $L - C_3 - mC_1 - nC_2$	$\alpha R_1 - C_1 + mC_1$ $\beta R_2 - \gamma C_2 + n\gamma C_2$ $L_1 - C_3 - mC_1 - n\gamma C_2$
			Do not participate in the transition $1-y$	$-N - P$ $-C_2 + nC_2$ $P - Q - C_3 - nC_2$	$-N - P$ $-\gamma C_2 + n\gamma C_2$ $P - Q - C_3 - n\gamma C_2$
	Do not supervision $1-x$	Supply Chain Enterprise	Low Carbon Transition y	$R_1 - C_1$ $R_2 - C_2$ 0	$\alpha R_1 - C_1$ $\beta R_2 - \gamma C_2$ 0
			Do not participate in the transition $1-y$	$-N$ $-C_2$ $-Q$	$-N$ $-\gamma C_2$ $-Q$

3 Stability Analysis of Equilibrium Points in Tripartite Evolutionary Game System

In the realm of the supply chain's low-carbon transformation system, it is crucial to scrutinize the equilibrium point of the evolutionarily interactive system consisting of three entities: the government, MSCE, and LCTE. These replication dynamic equations are (1), (2), (3):

$$F(x) = x(1-x)(yzL - ymC_1 + yL_1 - yzL_1 - znC_2 - n\gamma C_2 + P - C_3 + zn\gamma C_2 - yP) \quad (1)$$

$$F(y) = y(1-y)(xmC_1 + \alpha R_1 - C_1 - z\alpha R_1 + xP + N) \quad (2)$$

$$F(z) = z(1-z)(xnC_2 + yR_2 - C_2 - xn\gamma C_2 - y\beta R_2 + \gamma C_2) \quad (3)$$

According to $F(x) = 0, F(y) = 0, F(z) = 0$, the equilibrium points of the system can be calculated as: $E_1(0,0,0), E_2(0,0,1), E_3(0,1,0), E_4(1,0,0), E_5(0,1,1), E_6(1,0,1), E_7(1,1,0)$, $E_8(1,1,1)$. The Jacobian matrix of the Tripartite evolutionary game system is shown in (4):

$$\begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{pmatrix} \quad (4)$$

In such cases, if the eigenvalues of the Jacobian matrix are negative, the matrix is proven to be negative definite. Consequently, it suffices to ascertain the eigenvalues of the Jacobian matrix at each equilibrium point. The corresponding eigenvalues are provided in the Table 2.

Table 2. Jacobian matrix eigenvalue

Equilibrium point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
$E_1(0,0,0)$	$-n\gamma C_2 + P - C_3$	$\alpha R_1 - C_1 + N$	$-C_2 + \gamma C_2$
$E_2(0,0,1)$	$-nC_2 + P - C_3$	$-C_1 + N$	$C_2 - \gamma C_2$
$E_3(0,1,0)$	$-mC_1 + L_1$ $-n\gamma C_2 - C_3$	$-\alpha R_1 + C_1 - N$	$R_2 - C_2 - \beta R_2 + \gamma C_2$
$E_4(1,0,0)$	$n\gamma C_2 - P + C_3$	$mC_1 + \alpha R_1$ $-C_1 + P + N$	$nC_2 - C_2 - n\gamma C_2 + \gamma C_2$
$E_5(0,1,1)$	$L - mC_1 - nC_2 - C_3$	$C_1 - N$	$-R_2 + C_2 + \beta R_2 - \gamma C_2$
$E_6(1,0,1)$	$nC_2 - P + C_3$	$mC_1 - C_1 + P + N$	$-nC_2 + C_2 +$ $n\gamma C_2 - \gamma C_2$
$E_7(1,1,0)$	$mC_1 - L_1 + n\gamma C_2 + C_3$	$-mC_1 - \alpha R_1 +$ $C_1 - P - N$	$nC_2 + R_2 - C_2 - n\gamma C_2$ $-\beta R_2 + \gamma C_2$
$E_8(1,1,1)$	$-L + mC_1 + nC_2 + C_3$	$-mC_1 + C_1 - P - N$	$-nC_2 - R_2 + C_2$ $+n\gamma C_2 + \beta R_2 - \gamma C_2$

According to the Lyapunov first discriminant method, the analysis of the Jacobian matrix eigenvalues of each equilibrium point in the table shows that it is impossible to directly judge the symbols of all eigenvalues. In this process, there are many factors that affect the strategic choices of MSCE, LCTE, and the government. The eigenvalues λ_3 of points $E_2(0,0,1)$ and

$E_6(1,0,1)$ are always positive, so the two points are unstable points. In the remaining points, according to practical significance, the balance points that need special explanation are $E_8(1,1,1)$, $E_7(1,1,0)$, and $E_4(1,0,0)$. This paper takes $E_8(1,1,1)$ as an example for simulation analysis.

4 Simulation analysis

To verify the stability of the Tripartite evolutionary game, the model assignment is based on the ideal stable state $E_8(1,1,1)$ of the system, combined with the actual situation of the low-carbon transformation of the supply chain, and numerical simulation is carried out using Matlab, setting $R_1 = 50 R_2 = 30, C_1 = 20, C_2 = 10, C_3 = 5, m = 0.3, n = 0.3 \alpha = 0.5, \beta = 0.5, \gamma = 0.5, L_1 = 30, L = 50, P = 20, N = 20$,Substitute the selected data set into the model and perform multiple evolutions through simulation as shown in the following Figure 1:

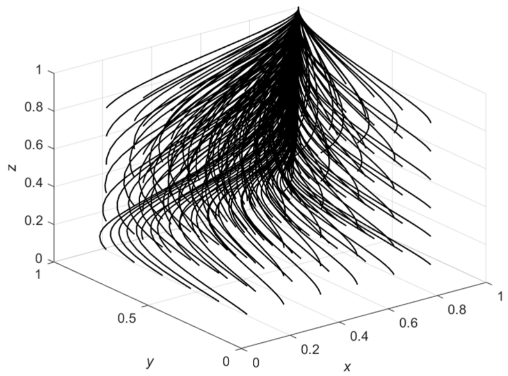

Fig.1. Simulation results of multiple evolutions of selected data sets

Figure 1 shows that the stable equilibrium point $E_8(1,1,1)$ is obtained from the simulation results, and there is only one evolutionary stable strategy combination: the government chooses supervision, the MSCE choose to participate in the low-carbon transformation of the supply chain, and the LCTE choose to actively participate in the low-carbon transformation of the supply chain. On this basis, the impact of R_1 and R_2 on the evolutionary game process is first analyzed. On the basis of the selected data set, we select R_1 as 50, 100 and 150, R_2 as 30, 50 and 70 respectively, and obtain three sets of control results, as shown in Figure 2.

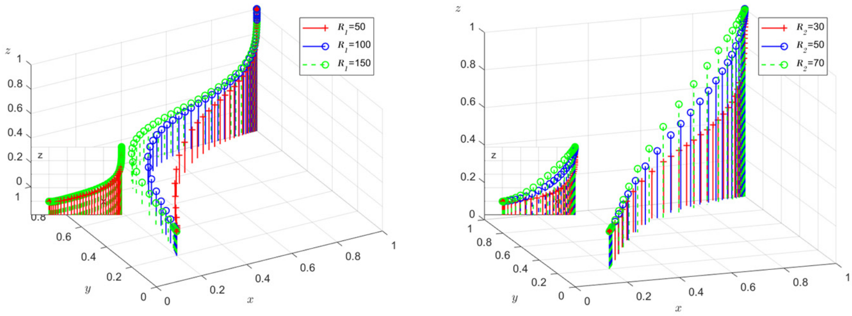

Fig.2. The impact of supply chain low-carbon transformation revenue R_1 and R_2

As shown in Figure 2, in the process of evolving to stable point $E_8(1,1,1)$, the increase in the benefits obtained by MSCE from the low-carbon transformation of the supply chain can significantly accelerate the evolution speed of MSCE' stable choice to participate in the low-carbon transformation. With the increase of R_1, the probability of MSCE choosing to participate in the green and low carbon transformation of the supply chain increases, and the probability of LCTE choosing to actively participate in the green and low carbon transformation of the supply chain also increases. Therefore, increasing the benefits obtained by MSCE from low-carbon transformation is conducive to promoting the low-carbon transformation of the supply chain. Increasing the benefits that LCTE derive from the low-carbon transformation of the supply chain can accelerate the rate of evolution of stable choice and active participation of LCTE. With the increase of R_2, the probability of LCTE choosing to actively participate in the low-carbon transformation of the supply chain increases. Therefore, increasing the benefits that LCTE obtain from the low-carbon transformation of the supply chain is conducive to promoting LCTE to actively participate in the low-carbon transformation of the supply chain.

Secondly, the impact of changes in C_1 and C_2 on the evolutionary game process is analyzed. On the basis of the selected data set, three sets of control results are obtained by taking C_1 as 20, 30, 40 and C_2 as 10, 20 and 30, respectively, as shown in Figure 3:

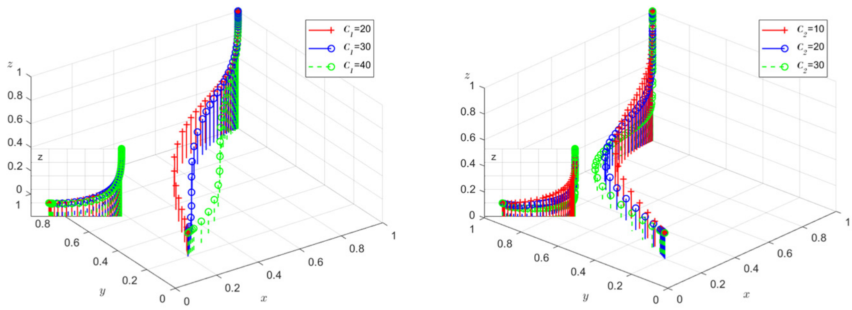

Fig.3. The impact of supply chain low-carbon transition costs C_1 and C_2

As shown in the Figure 3, in the process of the Tripartite game evolving to the stable point $E_8(1,1,1)$, the increase in the input cost required by the MSCE to participate in the low-carbon transformation will slow down the evolution speed of the MSCE to choose to participate in the low-carbon transformation of the supply chain. With the increase of C_1, the probability of MSCE choosing to participate in the low-carbon transformation of the supply chain decreases, and the probability of government choosing supervision and LCTE choosing to actively participate decreases. Therefore, in order to promote the low-carbon transformation of the supply chain, it is necessary to reduce the input cost of MSCE participating in the low-carbon transformation of the supply chain. The increase in the input cost of LCTE will slow down the evolution speed of LCTE to actively participate in the low-carbon transformation of the supply chain. With the increase of C_2, the probability of LCTE choosing to participate in the low-carbon transformation of the supply chain decreases, and the probability of the government choosing supervision decreases. Therefore, in order to promote the low-carbon transformation of the supply chain, it is necessary to reduce the input cost of LCTE participating in the low-carbon transformation of the supply chain.

On the basis of the selected data set, we select $m = n = 0.3, m = n = 0.5$ and $m = n = 0.7$, and obtain three sets of control results, as shown in Figure 4.

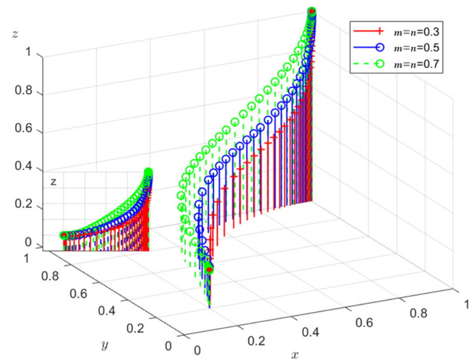

Fig.4. The extent and impact of government subsidies m and n

As shown in Figure 4, in the process of the Tripartite game evolving to the stable point $E_8(1,1,1)$, the increase in government subsidies for the input costs of both parties will accelerate the stable choice of MSCE to participate in the low-carbon transformation of the supply chain and the stable choice of LCTE to actively participate in the low-carbon transformation of the supply chain. With the increase of m and n, the probability of MSCE choosing to participate in the low-carbon transformation of the supply chain increases, and the probability of LCTE choosing to actively participate in the low-carbon transformation of the supply chain increases. Therefore, the government's subsidy policy is crucial to promoting the low-carbon transformation of the supply chain. To promote the green and low carbon transformation of the supply chain, the government can take appropriate measures or increase policy support to indirectly reduce the input costs required by both parties.

Finally, the influence of P on the three-party evolutionary game process is analyzed, and on the basis of the selected data group, P is selected as 20, 50 and 80, respectively, and three groups of control results are obtained, as shown in Figure 5.

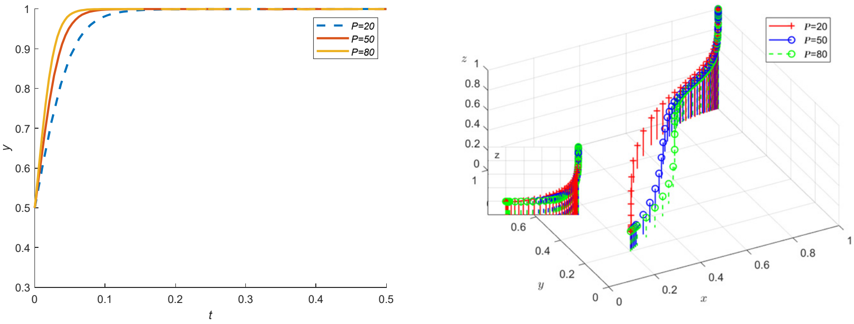

Fig.5. The impact of government penalties P

As shown in Figure 5, the left side of the figure shows the impact of the government's punishment on the probability of MSCE choosing to participate in the low-carbon transformation of the supply chain. In the process of the Tripartite game evolving to stable point $E_8(1,1,1)$, the increase of the government's punishment will accelerate the government's stable choice of supervision and the stable choice of MSCE to participate in the low-carbon transformation of the supply chain. With the increase of P, the probability of the government's choice of supervision increases, and the probability of MSCE choosing to participate in the low-carbon transformation of the supply chain increases. Therefore, in order to promote the low-carbon transformation of the supply chain, the government can adopt or increase penalties, such as carbon tax, environmental pollution fines, etc. Overall, factors such as the introduction cost and revenue of low-carbon technologies for MSCE, the R&D cost of LCTE, revenue and credible government revenue, green economic benefits and penalties will have an important impact on the final strategic choice of the three parties.

5 Conclusion

Based on the realistic background of the low-carbon transformation of the manufacturing supply chain, this paper has established a tripartite evolutionary game model of the MSCE, government and LCTE on the premise of the bounded rationality of the players, and focuses on the decision-making evolution mechanism of each entity in the process of low-carbon transformation of the supply chain. The results show that in the process of low carbon supply chain transformation, each parameter has different effects on the strategic choice of the players in the game. The degree of government subsidies, the performance benefits of low-carbon transformation, and the degree of government penalties are positively correlated with the likelihood that the collaborative innovation system will evolve to $E_8(1,1,1)$. The R&D costs required by LCTE and the introduction costs of low-carbon technologies and equipment required by MSCE are negatively correlated. The degree of government penalties can not only accelerate the speed of government selection and supervision, but also improve the speed of MSCE choosing to participate in the low-carbon transformation. Therefore, it is possible to promote multi-subject participation in the low-carbon transformation of the supply chain by increasing government subsidies and penalties, reducing the cost of enterprise transformation, and speeding up the process of low-carbon transformation of China's manufacturing supply chain.

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